Method for Updating an Earth Model Using
Measurements Gathered During Borehole Construction

FIELD OF THE INVENTION:

5   The present invention relates to the field of drilling oil and gas wells. In particular, the invention relates to a method for updating an earth model during construction of the well.

10   BACKGROUND OF THE INVENTION:

         Earth models contain data which characterise the properties of, and surfaces bounding, the geological features which form the earth's sub-surface, such as rock formations and faults. They are used to
15   assist operations occurring in the earth's sub-surface, such as the drilling of an oil or gas well, or the development of a mine.

         The domain of applicability of an earth model varies greatly and should be considered on a case by
20   case basis. Some earth models are applicable only in the near vicinity of a particular oil or gas well, or mine. Others may be valid for an entire oil or gas field, or perhaps even over a region such as the North Sea or Gulf of Mexico.

25   The data in an earth model consists of measurements gathered during activities such as the seismic, logging or drilling operations of the oil and gas industry, and of interpretations made from these measurements. The data may be gathered above, on, or
30   below the earth's surface.

As the duration or number of sub-surface operations increases, more data is gathered. This data can be used to amend the relevant earth model, with the aim that it should characterise the geology and

5   properties ever more accurately. Clearly, it will be conducive to the efficiency of these operations if amendments which enhance the accuracy of the earth model are made as quickly as possible, or appropriate.

The oil and gas industry's traditional

10   approach to amending earth models has not had a real-time element, apart from using formation integrity, leak-off or extended leak-off tests, or equivalent circulating density (ECD) data in the case of drilling fluid (commonly referred to as "mud") loss while

15   drilling, to constrain the minimum principal in-situ stress. See e.g., Addis et al., 'A comparison of leak-off test and extended leak-off test data for stress estimation', paper SPE/ISRM 47235 presented at the 1998 Eurock Rock Mechanics in Petroleum Engineering

20   Conference, Trondheim, July 8-10 (hereinafter "Addis et al., 1998"). Measurement-while drilling (MWD) data, logging-while drilling (LWD) data, wireline logs, results from tests performed on core, drilling experience and perhaps other information are used to

25   amend the relevant earth model using techniques identical to those used to generate the original version of the earth model. An example of these conventional techniques are described in a publication by Schlumberger Educational Services entitled 'Log

30   interpretation principles/applications', Houston, Texas

(1987), incorporated herein by reference and hereinafter referred to as ·"(Schlumberger, 1987)".

This traditional approach has been enhanced in order to improve the handling of very severe
5   wellbore instability problems in the Cusiana field in Colombia. See, Last, N., Plumb, R.A., Harkness, R., Charlez, P., Alsen, J. and McLean, M.: 'An integrated approach to evaluating and managing wellbore instability in the Cusiana field, Colombia, South
10 America', paper SPE 30464 presented at the 1995 Annual SPE Technical Conference, Dallas Oct. 22-25, incorporated herein by reference and hereinafter "Last et al. (1995)." Last describes an integrated approach to evaluating and managing wellbore instability. An
15 earth model was constructed using data from existing wells, together with results obtained using a computational analysis tool which modelled the geological structure and the in-situ stress state. This allowed the upper and lower bounds to the drilling
20 fluid density to be estimated, provided that the well trajectory was specified, using standard techniques.

As a well was drilled, a data acquisition programme which included cavings monitoring and measurements-while-drilling allowed the failure
25 mechanisms of the rock formations to be characterised. and as well as the identification and implementation of appropriate drilling practices. This led to faster, more efficient, well construction. The earth model was updated after a well or hole section had been completed
30 using all available data, particularly (a) downhole images of borehole geometry, fractures, faults and

bedding, (b) stress measurements such as extended leak-off tests, (c) results from tests made on core, and (d) four-arm calliper logs, where available. Measurement-while-drilling techniques were used to characterise

5   time-dependent hole geometry in particular hole intervals.

The approach of Last *et al.* (1995) enhanced the analysis of formation instability that can be made while drilling, with the minimum horizontal stress also

10 being updated in real-time. The understanding of the nature of the formation instability led to improved drilling practices allowing the wells they studied to be constructed much more efficiently.

However, the approach of Last *et al.* (1995)

15 has many limitations, including the following. First, no constitutive parameter or component of the in-situ stress state, other than the minimum principal stress, was updated in real-time. Such parameters were updated after drilling had been completed, using measurements

20 made by wireline tools, in addition to the data gathered in real-time. Second, LWD measurements, such as resistivity and sonic, were not extensively used. This inhibited the diagnosis of the instability mechanisms. Due to these limitations, it was not

25 possible to quantify amendments to drilling practices, apart from updating the value of ECD above which drilling fluid is lost to the formation.

SUMMARY OF THE INVENTION:

30   Thus, it is an object of the present invention to provide a method to increase the

efficiency with which an oil or gas well can be
constructed.

It is a further object of the present
invention to provide a method in which amendments that
5   enhance the accuracy of the earth model are made
quickly and efficiently.

It is a further object of the present
invention where one or more inconsistencies are
identified to provide a method of selecting which
10   component or components of an earth model to update.

According to the present invention the
efficiency with which an oil or gas well is constructed
can be enhanced by updating the relevant earth model
using real-time measurements of the effective density
15   of the drilling fluid and at least one other parameter.
Updating the earth model need not occur on a continuous
basis, but on a timescale appropriate to this
construction process. As used herein the term "real-
time" is defined to mean as the well or borehole is
20   being constructed. That is, the data acquisition can
occur continuously (e.g. measurement while drilling
data), or at discrete times (e.g. palaeontological
analysis of rock carried by the drilling fluid from the
wellbore) and still be considered "real-time".

25   A method for updating an earth model is
provided that includes obtaining an earth model used
for predicting potential problems in drilling of a
borehole having a predetermined trajectory.
Evaluations of the state of the borehole and local
30   geological features are obtained which are based on the
earth model. Data is received that has been gathered

during the construction of the borehole. The evaluations are compared with a diagnosis of the state of the borehole and local geological features to identify at least one inconsistency. A component of

5   the earth model is identified that is both related to the identified inconsistency and has a high degree of uncertainty. The selected component of the earth model is then updated prior to completing construction of the borehole using the received data.

10   Preferably, the evaluations of the state of the borehole and local geological features are predictions of one or more conditions under which the borehole will fail, and they are obtained by combining the earth model with the predetermined trajectory of

15   the borehole.

Preferably, the process is repeated until a sufficient match exists between the predicted failure conditions and the diagnoses of the borehole.

Preferably, the earth model component that

20   will be updated is selected by first identifying components of the earth model that are relevant to the identified inconsistency and then ranking the identified components according to the degree of uncertainty. The component selected is preferably

25   updated using the minimum changes needed to eliminate an identified inconsistency.

Preferably, the received data includes the effective density of the drilling fluid used in the construction of the borehole and one at least other

30   parameter, and the selected component is updated by

using the effective density and at least one other
parameter.

The invention is also embodied in a method
for drilling a borehole using an earth model that is
5   updated according to the invention. The invention is
also embodied in a computer readable medium that is
capable of causing a computer to update the earth model
according to the invention.

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BRIEF DESCRIPTION OF THE DRAWINGS:

Figure 1 illustrates the construction of a
borehole according to a preferred embodiment of the
15   invention;

Figure 2 shows a flow chart of a method of
updating an earth model, according to a preferred
embodiment of the invention;

Figures 3a and 3b show examples of angular
20   cavings that have become detached from the wellbore
wall when breakouts occur;

Figure 4 is a schematic representation of
breakouts and drilling induced fractures in a vertical
well embedded in an isotropic rock formation;

25   Figure 5 is a flow chart illustrating in
greater detail the preferred method of updating the
earth model according to the present invention;

Figure 6 illustrates an example of the
minimum principal in-situ stress in an earth model;

30   Figure 7 illustrates an example of the mud
window estimated prior to drilling a well;

Figure 8 illustrates an example of drilling
hazards derived from an analysis of experience drilling
offset wells and the well trajectory shown in Figure 9;

Figure 9 illustrates the trajectory of the

5   well used in the examples of Figures 6-11;

Figure 10 illustrates the in-situ stress
state prior to drilling the well used in Figures 6-11;
and

Figure 11 illustrates an example of the

10   formation strength in the example of figure 6-11.

DETAILED DESCRIPTION OF THE INVENTION:

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The present invention advantageously
increases efficiency with which an oil or gas well is
constructed by updating the relevant earth model using
real-time measurements. Preferably, the real-time

20   measurements are ECD and at least one other parameter,
which can gathered using common commercially available
methods. For example, the ECD data may be obtained
using such as Schlumberger's Annular Pressure While
Drilling APWD measurements. See e.g., Schlumberger

25   Oilfield Review: 'Using Downhole Annular Pressure
Measurements to Improve Drilling Performance', Sugar-
Land, Texas, Winter 1998 incorporated herein by
reference and hereinafter referred to as "Schlumberger
(1998)".

30   Figure 1 illustrates the construction of a
borehole according to a preferred embodiment of the

invention. Borehole 102 is being drilled into Earth
100. Rig 104 is located at the surface and is used to
support the drilling operation. Drill bit 110 is
located at the bottom of the borehole and is connected
5   to the rig via drill string 106. Also shown is a LWD
or MWD tool 108 that is capable of making measurements
during the drilling operation. The dashed line 114
shows the planned borehole trajectory. Offset well 116
is also shown, along with rig 118. Although in the
10   example of Figure 1 the boreholes are shown being
drilled on land, the invention is also applicable to
offshore drilling operations. Control station 112 is
shown schematically, and contains one or more computers
that are used to store the earth model, receive
15   measurements from the downhole tools, and update the
earth model according to the preferred embodiments
described herein. The control station 112 is shown to
be located near the rig 104, however in general the
control station can be located remotely.
20   Alternatively, some portions of the control station
could be located remotely while other portions are
located near to the borehole.

Figure 2 shows a flow chart of a method of
updating an earth model, according to a preferred
25   embodiment of the invention. In step 120, prior to
drilling a well and applying the invention, an earth
model is generated with seismic, logging and offset
well data using techniques which are publicly
documented (See, e.g., Last *et al.* (1995),
30   Schlumberger, 1987). The data contained in the earth
model is defined herein as the "components" of the

earth model. The types of data or components contained in an earth model typically consists of: (1) Surfaces bounding geological features, (2) Constitutive parameters of the rock. These describe the mechanical

5 response of rock under load, (3) Stress state and pore pressure, (4) Nature and severity of the drilling hazards associated with each geological feature and/or trajectory. The drilling hazards are categorised from a list which includes hole cleaning, sloughing, chemical

10 activity, undergauge hole, interbedded sequences, faults, naturally fractured formations, formations with weak planes, mobile formations and permeable formations (this list is not exhaustive and further categories can be envisaged), and (5) Any other parameter that may

15 prove to be useful for real-time analysis, such as gamma-ray measurements which characterise the radioactive nature of a formation.

In step 122, the earth model is combined with the planned well trajectory 124, in order to estimate

20 the upper and lower bounds to the drilling fluid density, together with the drilling hazards and their severity at discrete points along the trajectory. Step 122 may be accomplished using standard techniques, such as those outlined in Fjaer, E., Holt, R.M., Horsrud,

25 P., Raaen. A.M., and Risnes, R.: 'Petroleum Related Rock Mechanics', Elsevier, Amsterdam (1992), incorporated herein by reference and hereinafter referred to as "Fjaer *et al.* (1992)." More sophisticated analyses could also be used which may

30 involve concepts such as elastoplastic modelling. See e.g. Bradford, I.D.R., Fuller, J.A., Thompson, P.J.,

and Walsgrove, T.R.: 'Benefits of assessing the solids production risk in a North Sea reservoir using elastoplastic modelling', paper SPE/ISRM 47360 presented at the 1998 Eurock Rock Mechanics in

5 Petroleum Engineering Conference, Trondheim, July 8-10 Incorporated herein by reference and hereinafter referred to as "Bradford et al., (1998)." Although the earth model is shown to be generated in step 120 and the estimations performed in step 122, the earth model

10 and the estimates could be obtained through other means such as receiving them from an outside service provider.

As the well is being drilled, the nature and severity of instability mechanisms, together with the

15 conditions under which they occur, are identified, or diagnosed, in step 128. The extent of any instability, which is defined as the length of wellbore over which formation failure is occurring, may also determined. The diagnosis of step 128 can be carried out by the

20 method disclosed in Last et al. (1995). However, a more extensive use of real-time MWD and LWD measurements is preferably used for the diagnosis.

According to a preferred embodiment, in step 128, diagnosing the nature, severity and extent of

25 wellbore instability mechanisms should include the following considerations.

1. There should be sufficient familiarity, prior to commencing operations, with the upper and lower bounds of the drilling fluid density (these

30 define the "mud window") and the anticipated severity of any instabilities.

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2. The mud density and ECD should be monitored continuously, particularly in relation to the mud window calculations in order to assess the likely degree of breakouts and the possibility of mud losses.

5   When the mud is stationary, as is the case during connections, the ECD equals the mud density. During drilling, or while circulating off bottom, the ECD typically exceeds the mud density by up to 0.5-1.0 lb/gal. During trips, when equipment is being pulled up

10   and down the well, the ECD below the bit is typically 0-0.5 lb/gal less and more, respectively, than the mud density.

3. The behaviour of the drillpipe and bottom hole assembly (BHA), hole cleaning, rate of penetration

15   (ROP), trajectory, cavings rate and morphology, mud losses/gains and chemistry, together with resistivity, gamma-ray, compressional slowness and caliper LWD measurements should also be continuously monitored. It is then possible to conduct the following evaluations:

20   (a) Cavings analysis can provide a signal that the borehole is failing and indicates the troublesome formations. Tabular, angular or splintered cavings indicate that the nature of the instability is natural fracturing or weak planes, breakouts and over-

25   pressure, respectively. The cavings rate indicates the level of failure. However, if the hole cleaning is inadequate, not all of the debris generated by any instability may be discharged from the well, thereby masking the severity of the problem. This issue is

30   discussed fully below.

(b) Mud losses occur in naturally fractured zones, faults or drilling induced fractures. Such an event indicates that the fluid pressure in the annulus has exceeded the minimum in-situ principal stress. Mud gains indicate the pore pressure has exceeded the mud pressure or that previously lost mud is being returned to the wellbore due to fracture closure. Such an event allows the pore pressure estimate to be refined. In areas where there is chemical instability, a more comprehensive mud analysis programme may be required.

(c) Gamma-ray data enables formation boundaries to be identified. Some characterisation of the formation may also be possible, if the data is combined with other measurements such as resistivity.

(d) Resistivity measurements allows fracture identification. Schlumberger's LWD tool measures the resistivity at various depths (See e.g., Schlumberger (1998)); the degree of oil based mud invasion into water filled fractures can therefore be determined.

(e) Compressional slowness characterises pore pressure and formation strength.

(f) Caliper measurements of hole enlargement, if available, will identify the unstable formations.

(g) The ROP and hole cleaning efficiency form the key links between wellbore instability and operations. Rock debris in the annulus, resulting from drilling and/or wall failure, will increase if hole cleaning is inadequate, raising the risk of pack-offs, stuck pipe and tools lost in hole. For and explanation of these terms, see Bourgoyne, A.T., Chenevert, M.E.,

Millheim, K.K. and Young, F.S.: 'Applied Drilling
Engineering, SPE Textbook Series, Vol. 2 (1991),
incorporated herein by reference. The ability to clean
the hole is also related to the ROP. At sufficiently

5   high ROP's, the rate of influx of debris into the
annulus, from drilling and newly exposed rock which may
be failing, will exceed the rate at which material can
be discharged from the well, leading to the
consequences outlined above.

10   A reliable diagnosis of the instability
mechanism preferably uses all available data. If
tabular cavings, due to natural fracturing, are
observed, then the resistivity log should be checked
for evidence of mud invasion into fractures and the mud

15 records require examining for losses. Similarly, if
splintered cavings due to over-pressured formations are
seen then high gas levels, kicks or mud gains may also
be present. The observation of angular cavings due to
breakouts requires the debris levels in the hole to be

20 discerned. In all cases, the cavings volume should be
compared to the ECD and the degrees of tight hole and
restricted circulation to discern the effectiveness of
the hole cleaning and the severity of instability.

        In step 130, the states of the wellbore, and

25 geological features adjacent to it, that are predicted
using the earth model are compared with those diagnosed
using real-time data. If differences exist between the
predicted and diagnosed states then the earth model is
updated. The comparison of the estimated conditions

30 and the real time based diagnosis should be considered
to "match" when the two conditions are within a

reasonable range. For example, according to a
preferred embodiment, if the mud pressure at which
moderately severe breakouts occurred is not within 2
percent of the value estimated in step 122, then they

5   considered inconsistent and a "sufficient match" in
step 132 does not exist. However, the individual
thresholds for each compared condition will have to be
determined on a case-by-case basis.

     According to a preferred embodiment, real-

10   time data 126 includes measurements of the ECD and at
least one other parameter. Preferably, these
measurements are used in the comparison of diagnosed
states with predictions derived from the earth model in
step 130, and in the updating of the earth model, which

15   discussed more fully below.

     For example, in a vertical well, suppose the
ECD exceeds the estimated lower bound of the drilling
fluid density and that a steady stream of cavings is
being carried from the hole. If the cavings have an

20   angular morphology, then breakouts have occurred,
albeit at a higher than expected drilling fluid
pressure, as indicated by the ECD data. As the
pressure of the drilling fluid decreases, zones of
shear failure develop that are centred about the line

25   of action of the minimum horizontal in-situ stress. The
material in these zones eventually drops into the
wellbore, leading to the cavings shown in Figures 3a
and 3b. Conversely, as the drilling fluid pressure
increases, fractures develop centred about the line of

30   action of the maximum horizontal in-situ stress.

According to a preferred embodiment, following are four examples of situations in which there would be an insufficient match in step 132 and the earth model would therefore be updated:

5   1.   Breakouts occur, or the fluid is lost to the formation, at values of ECD that differ from those that are predicted;

           2.   The nature, severity or extent of the drilling hazards differ from their prognosis;

10   3.   Geological characteristics (e.g. the location of formation tops with respect to the trajectory) differ from their prognoses; or

           4.   Fluid or gas unexpectedly enters the wellbore indicating that estimates of the pore pressure

15 are inaccurate.

Referring again to Figure 2, in this example a sufficient match would not exist in step 132. Accordingly, the earth model would be updated in step 136. In this example, the in-situ stress state, the

20 formation strength, or both of these quantities should be amended so that the predicted and actual states match adequately.

According to a preferred embodiment, the components of the earth model that are the most

25 uncertain should be given priority in the updating process. This advantageously allows for the most efficient and accurate updating of the earth model. Figure 5 is a flow chart illustrating in greater detail the preferred method of updating the earth model

30 according to the present invention. Steps 150, 152 and 154 correspond to step 136 in Figure 2, whereas steps

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122, 130, 132 and 134 correspond to the same steps in both figures 2 and 5.

In step 150 the components that are relevant to the inconsistency are determined. In cases where

5   there are more than one inconsistency is identified in the comparison step 130, the most hazardous inconsistency is generally addressed first. In step 152 the relevant components identified in step 150 are ranked according to certainty. In other words, the

10   earth model components that are most unreliable are identified, and preferably, ranked in order of reliability. Alternatively, step 150 can be skipped and the ranking step 152 applied to all or some predetermined number of most uncertain components. The

15   goal of steps 150 and 152 are to identify the most unreliable or most uncertain components or parameters in the earth model so that the update can be focused on those components.

In step 154 the most uncertain components are

20   updated. According to a preferred embodiment, the components that are updated are ideally altered by the smallest degree needed to allow matching of the predicted and measured components.

As discussed above, in steps 122, 130, 132,

25   and 134 failure conditions are estimated, and comparison is made to determine if there is a sufficient match between the estimated conditions and the real time diagnosis. If there is a sufficient match, no further changes are made to the earth model.

30   When a sufficient match is not found, steps 152, 154 122, 130 and 132 are repeated as shown in Figure 5.

When step 152 is being repeated, the recently amended
components are preferably re-ranked as being more
certain due do their recent amendment. When step 122
is being repeated, the well failure conditions are re-
5 estimated using the updated components.

Following is an example the process described
in Figure 5. If real-time compressional slowness data
is available through use of the appropriate LWD tool,
then the formation strength estimate can be inferred
10 from this measurement and the formation strength is
assumed to be the most reliable component in step 154.
In step 154, the minimum change to the in-situ stress
state (actually the maximum principal in-situ stress,
as the minimum principal in-situ stress is constrained
15 using a combination of fluid loss and ECD data) should
then be made which allows the predicted and measured
pressures at which breakouts occur to adequately match,
with the latter determined using ECD data. If real-
time compressional slowness data is not available, then
20 it is assumed that the formation strength is the most
unreliable (or least certain) parameter or component in
step 152. In step 154, the formation strength is
updated until prediction and reality match adequately.

Following are further examples of how the
25 earth model updating processes in steps 150, 152 and
154 could be carried out, according to the invention.
In particular, if breakouts or fluid losses do not
occur as anticipated then the in-situ stress state and
formation strength predictions should be amended. More
30 specific examples are as follows.

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Suppose the ECD exceeds the anticipated minimum principal in-situ stress without fluid loss. The minimum principal in-situ stress should be amended to be equal to the maximum ECD encountered over the

5 appropriate interval. The new estimate of the minimum principal in-situ stress will be a lower bound to the true value, but will be more accurate than the existing prediction.

Suppose fluid loss occurs at an ECD lower

10 than the minimum principal in-situ stress. The minimum principal in-situ stress should be set to the ECD at which the fluid loss occurred. This will require a comparison of the time based ECD and drilling fluid volume logs.

15 Suppose breakouts occur at a value of the ECD higher than the minimum value predicted; it is then either in-situ stress state, the formation strength, or both of these quantities that should be amended. If the formation strength can be inferred from real-time

20 measurements, such as compressional slowness data from the appropriate LWD tool or indentation tests on cuttings, then it may be assumed to be the most reliable parameter. The minimum change to the in-situ stress state (actually the maximum principal in-situ

25 stress, as the minimum principal in-situ stress is constrained through fluid loss observations) is then made which allows prediction to match reality. If the formation strength cannot be inferred from real-time measurements, it should be assumed to be the most

30 unreliable parameter and then amended until there is an adequate match between prediction and reality. The

method of updating the in-situ stress or formation
strength is identical in both cases: it requires that
these parameters are amended until the output of the
models that has used to estimate the bounds to the
5 drilling fluid density agrees with the real-time
measurement. This is an iterative process.

Breakouts occurring at values of ECD that are
lower then the predicted minimum values are expected.
No change is therefore made to the mechanical earth
10 model.

Suppose the nature, severity or extent of the
drilling hazards, or geological characteristics, differ
from their prognoses, or fluid or gas unexpectedly
enters the wellbore. The diagnostic techniques outlined
15 in above could be used to detect these events and the
earth model could then be directly updated without
further computation, although the ECD should be used to
assess the severity of the drilling hazard and the
expectation of fluid or gas entry into the wellbore.
20 Other real-time information, such as palaeontological
analysis of cavings or LWD resistivity data, should be
used to assess the extent of any instability associated
with the wellbore or adjacent geology.

The following example further illustrates how
25 an earth model may be updated. After a well had been
drilled to a depth of 2000m TVD (true vertical depth),
it was decided to pull the drilling equipment out of
the well. However, during this process 12 barrels of
drilling fluid were lost to the formation. The real-
30 time ECD measurement showed that this occurred at a
pressure equivalent to 15.35 lb/gal. Figure 6

illustrates an example of the minimum principal in-situ
stress in an earth model, according to a preferred
embodiment of the invention. As shown in Figure 6, the
minimum principal in-situ stress was therefore revised

5 to be the equivalent of 15.35 lb/gal for the entire
region above 2000m TVD.

As discussed, estimates along the trajectory
of the upper and lower bounds of the drilling fluid
density, together with the nature, severity and extent

10 of the drilling hazards, allow the states of the
wellbore, and geological features adjacent to it, to be
predicted while the well is constructed. Examples of
these are shown in Figures 7 and 8 for a well drilled
in the North Sea. Figure 7 illustrates an example of

15 the mud window (i.e. allowable drilling fluid
densities) estimated prior to drilling the well.
Drilling with a mud (i.e. fluid) whose density falls to
the left of the solid line leads to breakouts.
Conversely, drilling with a mud whose density falls to

20 the right of the thick broken line will cause fluid
loss into the formation. The vertical axis denotes the
length of wellbore below the drilling rig floor.
Figure 8 illustrates an example of drilling hazards,
derived from an analysis of experience drilling offset

25 wells, and the well trajectory shown in Figure 9. In
figure 8, the severity of the hazard is shown as a
"traffic light" classification. The vertical cross
hatch indicates that the symptoms of the instability
are present but insignificant: no remedial action is

30 necessary. The horizontal cross hatch indicates that
remedial action should be taken because the instability

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is significant and could become serious. The diagonal
cross hatch indicates that the instability is likely to
result in loss of the well. The problem should be
avoided, otherwise immediate remedial action should be

5   taken. Figure 9 illustrates the trajectory of the well
used in the examples of Figures 6-11. The Northerly
and westerly directions are annotated (N and W,
respectively). The vertical scale is true vertical
depth below the drilling rig floor. Figure 10

10   illustrates the in-situ stress state prior to drilling
the well used in Figures 6-11. In Figure 10, the
symbols σ_V, σ_h and σ_H denote the vertical, minimum
horizontal, maximum horizontal stresses, respectively
and P_p is the pore pressure. TVD denotes true vertical

15   depth with respect to the drilling rig floor. Figure
11 illustrates an example of the formation strength in
the example of figure 6-11. The formation strength
shown in Figure 11 is defined by the two parameters
required to define the Mohr-Coulomb failure criterion.

20   UCS and φ denote the uniaxial compressive strength and
friction angle respectively.

     The upper and lower bounds to the drilling
fluid density may be derived by combining a prediction
of the stress state around the wellbore embedded in an

25   isotropic, homogeneous medium using an undrained linear
elastic model with a Mohr-Coulomb failure criterion
(Fjaer et al., 1992), or through use of other
techniques. The lower bound represents the minimum ECD
that is required in order to prevent breakouts. The

30   upper limit represents the maximum ECD that is

allowable before rock at the wellbore wall fractures or
fluid is lost to the formation. These bounds may,
however, have different physical interpretations if
more sophisticated models (for example, the deformation
5   of a salt formation) are used to derive them.

While preferred embodiments of the invention
have been described, the descriptions and examples are
merely illustrative and are not intended to limit the
present invention.
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